FIRE-HAZARD AND FIRE-RISK ASSESSMENT OF FIRE-RETARDANT POLYMERS

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I. INTRODUCTION

The previous chapters have all, in one way or another, addressed the "hard science" aspects of fire-retardant polymers. Physics and chemistry defined the relevant science, which provided the base for engineering the product design or testing. But what is the value of all that work, expressed in terms nonscientists can understand? To answer that question, one needs to use fire-hazard or fire-risk assessment.

Imagine all the fires that could occur as a universe of possibilities. Every fire has a probability of occurrence and an expected degree of loss, or severity, if it occurs. Reduce the probability—make the product harder to ignite—and the danger from unwanted fire is reduced. Reduce the expected severity—force the burning product to spread flame less rapidly or to burn less intensely, for example—and the danger from unwanted fire is reduced. Fire-hazard assessment and fire-risk assessment are two analytical methods of quantifying the implications for fire danger of product choices.

II. FIRE HAZARD VERSUS FIRE RISK

"Fire hazard" is potential for harm due to fire. Because it may not be possible to measure "potential" in a consistent and stable fashion, "fire hazard" is normally equated to severity of fire—the expected degree of loss. This severity will be defined in part not only by the characteristics of the product(s) involved in fire but

also by a multitude of conditions and factors that are collectively referred to as a *scenario*.

The scenario includes details of the room dimensions, contents, and materials of construction, arrangement of rooms in the building, sources of combustion air, position of doors, numbers, locations, and characteristics of occupants, and any other details that will have an effect on the outcome of interest.

How does the analyst determine the expected loss—the severity or harm—for a particular fire scenario? This determination can be made by expert judgment. It can be made using probabilistic methods and data on past incidents. It can be made using full-scale fire tests designed to reproduce the scenario in every detail; or it can be made by deterministic means, such as fire models. The trend today is to use models wherever possible, supplemented where necessary by expert judgment. Methods based exclusively on data from past fires cannot address new products, whereas calibrating a full-scale fire test to a specific scenario may be impractical and prohibitively expensive.

Hazard analysis can be thought of as a component of risk analysis; that is, a risk analysis is a set of hazard analyses that have been weighted by their likelihood of occurrence. The total risk is then the sum of all of the weighted hazard values; or, depending on the risk measure used, risk may be defined as the probability of having a fire whose hazard exceeds a specified threshold. In the insurance and industrial sectors, risk assessments generally target monetary losses, as these dictate insurance rates or provide the incentive for expenditures on protection. In the nuclear-power industry, probabilistic risk assessment has been the basis for safety regulation. Here, they most often examine the risk of a release of radioactive material to the environment, from anything ranging from a leak of contaminated water to a core meltdown.

In the field of product liability, the importance is on hazard and not necessarily on risk. Even if it can be shown to be extremely rare, an event in which a product causes harm results in awards proportional to the consequences.

Fire-hazard or fire-risk assessment in support of regulatory actions generally looks at hazards to life, although other outcomes can be examined as long as the condition can be quantified. For example, in a museum or historical structure, the purpose might be to avoid damage to valuable or irreplaceable objects or to the structure itself.

Conducting a fire-hazard or fire-risk assessment of a fire-retardant polymer is a special case of the more general topic. The treatment is meant to reduce ease of ignition, reduce burning or flame-spread rate, or reduce smoke emission, all without making any other property sufficiently worse, so that the overall hazard or risk is reduced. If the fire-retardant product is not the first or second item ignited, chances are that the product's role in the scenario is minor. For product liability purposes, it is generally sufficient to show that the presence of the product did not contribute to the outcome.

III.   STEPS IN A PRODUCT FIRE-RISK
OR FIRE-HAZARD ANALYSIS

The steps and substeps briefly described below parallel current thinking at U.S. standards-writing organizations, notably the American Society for Testing and Materials (ASTM), and previous global reviews of approaches to this subject, particularly as synthesized by Bukowski and Tanaka (1). Later sections expand on techniques to be used in executing these steps.

A.   Define the Scope of Products to Be Analyzed

1.   Define the product or, more typically, the product class to be evaluated.
2.   Specify where and how the product is used. For example, a standard for floor coverings would not include all uses of carpeting, because carpeting is sometimes used as a wall covering. The specification of application will not only limit the range of product characteristics but will also specify or limit the input parameters used to identify fire scenarios in which the product may play a role.
3.   Specify the property in which the product is used. The end use or principal activity in a property defines it as an *occupancy*, which will imply a variety of characteristics and conditions in the environment of the product. For example, a risk or hazard analysis of upholstered furniture in homes will be different from a risk or hazard analysis of upholstered furniture in offices, and both will be different from a risk or hazard analysis of upholstered furniture in hotels. The types of pieces used are different, the applicable standards are different, the mix of fires they could be exposed to are different, and the mix of people likely to be present (and their capabilities) are different.

B.   Specify Goals, Objectives, and Measures
of Loss, Hazard, or Risk

1.   Specify goals in terms of acceptable target outcomes, usually in terms of types of harm to be prevented, minimized, or otherwise reduced. Life safety, defined in terms of fatal injury or other health effects, is usually the principal goal. Property protection, avoidance of indirect loss, and protection of heritage and the environment are other typical goals.
2.   Specify objectives, which are more specific means to the ends which are the goals. If objectives are stated in terms of the systems and features that engineers design, they are called functional objectives. Alterna-

tively, objectives may be stated in terms of events (e.g., flashover) or other physical conditions in fire.

3. Specify or quantify goals and objectives in the form of performance criteria or other measures of loss or harm. When doing so, there are a range of types of measures. Some measures, called end measures, are meaningful in and of themselves but are very difficult to predict in models or measure in tests (e.g., monetary damages, injuries). Some measures are easily predicted in models or measured in tests, but they are not meaningful in and of themselves (e.g., temperature or toxic gas concentrations or obscuration for particular areas or volumes). Typically, models must be used to convert readily measureable quantities to end measures of loss.

C. Set Assumptions

1. Set assumptions covering all aspects of building, occupant, system, feature, fuel load, modeling, or other elements affecting the outcomes that are not defined either by the product specifications (for the product being assessed) or by the scenarios, which address factors that vary.

2. For fire-risk assessment, set assumptions in terms of *average* conditions (or, if necessary, *typical* conditions), in order to predict overall risk—severity weighted by probability.

3. For fire-hazard assessment, set assumptions in terms of *conservative* conditions, in order to predict what *might* happen—how bad it could be—in the worst scenarios deemed to be fair challenges to the design of the product.

D. Select and Specify Fire Scenarios

A scenario is a set of details about the initiating conditions and early growth of a fire that are needed as input conditions to a test method, fire model, probability or other calculation. This may include the following:

1. Location and characteristics of the initial fuel and initial heat source. Some scenarios will address the ignitability of the fire-retardant product, and these will specify only the heat source. Other scenarios will address the role of the fire-retardant product as a secondary fuel package, and these will fully specify the initial fire.

2. Proximities and characteristics of other fuel packages near the first ignited item.

3. If fire growth or effects beyond the first affected room or area are important to the estimation of the chosen measures of loss, then complete descriptions of those other areas will be needed, including spatial dimensions, fuel load, thermal properties of room linings, barriers, and openings connecting areas, occupants, and damageable property.
4. Fire-protection systems must be specified for any areas to be modeled.

E. Identify Test Methods, Models, and Calculation Methods

The models needed will depend, in part, on the scenarios to be addressed, but the models listed below include the major modeling components included in most of the major modeling packages now in use. Each model has implications for data needs, including fire tests and statistical data bases. (See Ref. 2 for a more detailed review of available models.)

1. Fire-growth model
   (a) Model of rate of growth in terms of heat release rate, for example, as a function of fuel load and distances between items
   (b) Horizontal flame-spread model
   (c) Barrier failure (e.g., door, ceiling, window)
   (d) Exterior vertical flame-spread model
   (e) Flame-spread model in concealed spaces
   (f) Building-to-building flame spread
2. Smoke-spread model
   (a) Model of room filling
   (b) Model of spread between rooms
   (c) Flashover models, including timing of flashover and postflashover smoke spread
   (d) Model of spread via heating, ventilation, or air-conditioning system
3. Occupant behavior model
   (a) Model of automatic detection equipment performance
   (b) Model of how fire is discovered in the absence of automatic detection
   (c) Model of decision-making activities leading to decisions to egress or attempt rescue
   (d) Model of egress and rescue activities
4. Intervention models
   (a) Automatic suppression models, including timing of activation and effects on fire growth
   (b) Model of other suppression or extinguishment efforts and their effects (e.g., whether fire extinguishers will be used and to what effect)
   (c) Firefighter response models

5. Fire effects or outcome models
    (a) Predicted deaths and injuries due to fire effects in affected areas as a function of time
    (b) Structural damage or failure models
    (c) Predicted extent or monetary value of property damage
6. Ignition probability models (for fire-risk assessment only)
    (a) Fault tree, success tree, or event tree
    (b) Bayesian analysis of test results, historic fire probabilities, and other data.

In practice, many of these component models are rarely used. For example, a fire-risk or fire-hazard assessment of a burnable product may not need an elaborate analysis of intervention strategies, because the dominant scenarios may be those in which no prompt, effective intervention occurs. On the other hand, the modeling components used may identify a need for data for which no standardized source exists (e.g., burning properties of products in postflashover environments). It is not unusual, therefore, for the full calculation to require judgments by analysts, which must be checked through sensitivity analyses.

Bukowski and Tanaka (1) have proposed a conceptual scheme for standardizing the role of these expert judgments in fire-hazard and fire-risk assessment. Their scheme involves identifying groups of parameters and variables in the models and defining the acceptable sources of data for them, among which could be expert judgments.

Specifying and standardizing needed data sources is an essential part of the process of using fire-hazard or fire-risk assessment in a standard. The expectation is that instead of stating a standard in terms of specifications, the standard-setting process would specify outcome measures, models, and other calculation methods, modeling assumptions and input parameters, test methods and other data sources, and possibly the type of expertise required by those who run the models.

IV. DEFINE THE SCOPE OF PRODUCTS TO BE ANALYZED

Defining products includes specifying where and how they will be used. Property classes (i.e., occupancies) should have their primary definitions stated in terms of the categories defined in NFPA 901, *Uniform Coding for Fire Protection,* Chapter B, "Fixed or Specific Property Use" (3). Whenever occupancy scenarios can be defined using nationally representative, valid fire incident data, the analyst will have the strongest possible basis for estimating probabilities. The principal weakness of this data source involves the level of detail of readily available fire incident

data, which often falls well short of the detail needed to run the fire-hazard analysis portion of the method.

The scope should define a class of interchangeable items having a common function or application in a specified occupancy and with a range of allowable choices for composition. Specification of the product should be done in a way that facilitates use of existing data, from fire incident data to product test data.

For products made with fire-retardant polymers, this means that initial specification of the product by function should be based on the categories defined by NFPA 901, Chapter I, "Form of Material First Ignited" (3). Initial specification of the product by material composition should be based on the categories defined by NFPA 901, Chapter H, "Type of Material First Ignited" (3). A product, for example, a carpet, is defined as a floor covering made of certain materials, chosen to distinguish it from vinyl flooring, wood flooring, concrete slabs, and so forth.

Further specification of the product by function may be needed (e.g., selecting bookcases from the cabinetry group). In such cases, the nationally representative fire incident databases will not be sufficient to estimate probabilities. Other, special fire incident databases and expert judgment will be needed.

When calculating probabilities, be sure to include appropriate shares of fires involving products that were partially or wholly undefined (e.g., upholstered furniture fires should include shares of fires involving unknown-type furniture or unknown-type form of material first ignited and might include shares of fires involving unclassified furniture or unclassified form of material first ignited).

The range of items defined as examples of the product, which may be referred to as members of the product class, must, for analysis purposes, be reduced to a manageable number of subgroups. Each subgroup will be defined by a range of characteristics (e.g., all cellulosic versions of the product) but will be represented by one specific set of product fire characteristics. Ordinarily, these product fire characteristics will be identified from review of results of actual fire tests on one or more representatives of the product class.

V. SPECIFY GOALS, OBJECTIVES, AND MEASURES OF LOSS, HAZARD, OR RISK

Overall goals for fire safety tend to fall into one of the following categories:

- Prevent adverse health effects, particularly fatal injury, to people exposed to fire. Emergency responders are normally addressed separately and may be excluded from consideration.
- Prevent monetary losses due to direct property damage.
- Prevent indirect losses due to fire, such as business interruption, missed work, and temporary housing. The types of indirect losses will differ for

residential and nonresidential occupancies, as will the relative importance of direct damage and indirect loss.

- Prevent environmental damage. This may be damage due to fire, damage incidental to firefighting or other suppression activities, or damage associated with fire-prevention or fire-protection strategies. The negative impact of some fire retardants on recyclability of plastics could be addressed under the latter type of goal.
- Prevent harm to cultural heritage. This refers to historic buildings and similar structures for which fire damage may be more expensive or impossible to repair if historical authenticity is an objective.

The most natural context for fire-risk or fire-hazard assessment is a whole building, vehicle, or other built environment, because all fire prevention and fire mitigation strategies are available. It is possible to conduct a fire-risk or fire-hazard assessment of fire-retardant materials or fire-retarded products using overall goals. It also is possible to use the overall goals for a building or vehicle fire-risk or fire-hazard assessment and then set objectives supporting those goals as functional objectives, defined in terms of the various functions in the building. With such an approach, fuel load or contents and furnishings can be defined as a function, having its own objective(s).

The advantage of the fuel load objective approach is that it does not require the analyst to define scenarios, set assumptions, and model phenomena far away from the product of interest. Instead, it is possible to construct the outcome measures closer to the kinds of values traditionally derived from product fire tests. The disadvantage of the fuel load objective approach is that it tends to be difficult to execute unless you can specify characteristics at the level of an individual building. If one attempts to use this approach as a basis for qualifying products for an entire class of occupancies, then one is forced to develop all the same information on overall goals, assumptions, scenarios, and models that would have been needed for an assessment at the building level, in order to derive generic functional objectives.

For this reason, this chapter will discuss the elements of a full fire-risk or fire-hazard analysis of a building in which fire-retarded products may be the true subject of interest but will not be the only system or feature explicitly addressed in the analysis.

For measures of loss in fire hazard assessment, the measure will be a predicted severity value, such as predicted deaths. For fire-risk assessment, both severity and probability are important. Two common summary measures are expected loss (i.e., a sum over all scenarios of scenario probability times predicted scenario hazard) and probability of loss exceeding a certain threshold. Both measures can be calculated directly from nationally representative fire incident databases without the need for modeling or testing, provided that the product class

definition matches the categories used in those databases and, more importantly and less likely, provided one is concerned only with the product's role in fire as the first item ignited.

Therefore, for a variety of reasons one is usually forced to use test methods and models to develop probability estimates and fire-severity estimates more appropriate to the product class and product alternatives of interest. In such cases, much calculation effort can be saved if the problem lends itself to restatement in terms of measures of loss that can be measured in the laboratory and at the fire scene. Three examples are as follows:

- Probability of flashover and/or of flame spread beyond the room of origin
- Probability of fire ignition
- Probability that time to flashover exceeds x minutes (where x is chosen to reflect the expected arrival of suppression and rescue forces)

One approach that should usually be avoided is to try to measure loss in terms of the product's share of responsibility for overall fire severity. Such measures tend to be far too subjective and require answers to inherently unanswerable questions. For example, suppose a small trashcan fire leads to a large couch fire. If *either* the factors in the initial trash ignition or the burning properties of the couch are changed, no large fire would have resulted. How much loss should be assigned to the couch? There is no good answer to that question.

Instead, fire-risk or fire-hazard assessment should proceed through calculations of differences (i.e., fire risk or hazard with the product of interest versus fire risk or hazard with something else substituted for the product of interest).

From this perspective, one can see how fire-risk or fire-hazard assessment analyses can be constructed as extensions of past successful applications of fire modeling. For example, one of the earliest practical applications of the Harvard code was to the reconstruction of the 1980 MGM Grand Hotel fire. As suggested earlier, flashover was used as a well-defined event to focus the analysis, after it was shown that most of the fatal fire victims would have survived if flashover had been prevented. Professor Howard Emmons then used the model to rerun the fire with changes, considered individually, in the room of origin's ceiling covering, its benches and chairs, and the area's heating, ventilating, and air-conditioning (HVAC) arrangements.

If one wished to do a fire-risk analysis on, say, benches and chairs for dining areas of hotels, one could define a range of possible fire scenarios, do a similar Harvard code analysis of each, weight the consequences by the scenario probabilities, and thereby calculate an overall probability of flashover with two different choices of benches and chairs. The difference between the two probabilities would be a valid product fire-risk measure. A fire-hazard assessment would use fewer

scenarios but make each very challenging and require that the product "pass" every scenario.

A fire-hazard assessment of rigid nonmetallic conduit in hospital emergency systems, done by Benjamin/Clarke Associates, provides a rare example of circumstances where the product's share of fire loss can be validly used for analysis. Dr. Fred Clarke devised a realistic scenario designed to maximize the likelihood of significant product involvement in fire, by placing the initiating fire directly under the product, which was assumed to be exposed due to missing ceiling tile. This scenario was designed to put an upper bound on the product's share of fire loss in scenarios with significant loss.

VI. ASSUMPTIONS: CONSERVATIVE OR TYPICAL

Fire-risk or fire-hazard assessment requires the analyst to make assumptions. Some of the assumptions are embedded in elements of the analysis, such as the zone model's assumption that fire conditions in a room can be reasonably approximated by dividing the room into an upper layer and a lower layer. Some assumptions set boundaries to the analysis, such as an assumption that an effective local public fire department will respond within 5 min, which permits the designer to track fire development and effects for a limited period of time.

Many assumptions address building, occupant, fuel load, or system characteristics that do not vary from one scenario to another. These assumptions may be treated as scenario characteristics in one assessment and as assumptions in the next assessment. Therefore, the more detailed discussion of elements of scenarios, in the next section, also identifies most of the candidate assumptions.

There is a critical difference in the handling of assumptions in fire-risk assessment versus fire-hazard assessment. In fire-risk assessment, the purpose of the calculation is to predict what *will* happen. Challenging, high-severity scenarios must be addressed but must be given only as much or as little weight as the probabilities of those scenarios would justify. In fire-hazard assessment, the purpose of the calculation is to predict what *might* happen for which the designer is responsible. This is where concepts like "probable worst-care scenario" become redundant. Fire-hazard assessment need only address challenging, high-severity scenarios and will not discount the scenarios it addresses by their probabilities. However, some high-severity scenarios will be declared too challenging for a fire-hazard assessment. Thus, fire-hazard assessment takes an all-or-nothing approach to scenarios.

Fire-risk assessment, for these reasons, will assign more variables to scenarios and fewer to assumptions than will fire-hazard assessment. Fire-risk assessment needs to address all scenario possibilities. However, fire-risk assessment

will tend to set assumptions in terms of typical or average conditions. This approach better serves the purpose of fire-risk assessment, which is to predict what will happen. However, fire-hazard assessment will tend to set conservative assumptions. That approach better serves the purpose of fire-hazard assessment, which is to predict what might happen.

VII. SELECT AND SPECIFY FIRE SCENARIOS

Once the outcomes to be avoided are established, the task is to identify any scenarios that may result in these undesirable outcomes. Here, the best guide is experience. Records of past fires, either for the specific building or for similar buildings or class of occupancy, can be substantial help in identifying conditions leading to the outcome(s) to be avoided. Statistical data can provide valuable insight into the important factors. By contrast, anecdotal accounts of individual incidents are interesting but may not represent the major part of the problem to be analyzed.

Murphy's Law (anything that can go wrong, will) is applicable to major fire disasters (i.e., all significant fires seem to involve a series of failures that set the stage for the event). Thus, it is important to examine the consequences of things not going according to plan. What if automatic systems fail and the fire department does not respond? How bad would the result be? In a fire-hazard assessment, one may ask whether this scenario is so unlikely, or can be made so unlikely through inspection, maintenance, or backups that the scenario need not be considered. In a fire-risk assessment, one may ask whether the scenario's huge severity will be offset by a sufficiently low probability. If nothing else, such scenarios can help to identify the factors that mean the difference between an incidental fire and a major disaster.

Insights and factor identification do not suffice to construct and select specific scenarios. First, decide whether one wants typical/average scenarios or high-challenge/worst-case scenarios. The previous section on assumptions indicates when and why one will want each.

Second, select locations—typical or high challenge—for the fires. Location is a qualitative rather than a quantitative scenario characteristic, but it is often among the most important. High-challenge locations include those that will interfere with occupant movement (e.g., entrance ways, hallways or corridors, stairways), those that will lead to very rapid occupant injury (e.g., on a person or on his or her clothing), and those that are shielded from fire-protective systems or features (e.g., concealed spaces, exterior surfaces).

Third, for each of the scenario characteristics that follow, consider the possibility that the characteristic may need to be handled as a variable; that is, especially for fire-risk assessments, one may need to define a set of scenarios, each

having a different value of the scenario characteristic (e.g., a different rate of growth in the rate of heat release for the initial fire growth). Theoretically, of course, one might need to vary this scenario characteristic for every combination of other scenario characteristics. (For example, varying the rate of growth in the initial rate of heat release would not mean four scenarios instead of one but would mean four times as many total scenarios.) This will quickly become unmanageable.

In a fire-hazard assessment, one may be able to avoid this problem by consistently choosing conservative, even worst-case, values. In a fire-risk assessment, there are experimental design methods that serve the purpose of sampling among the many combinations.

For every scenario, each aspect of fire initiation and growth must be specified in such a way that (a) one can model, test, or otherwise calculate the fire-severity consequences of a fire with those specifications and (b) one can calculate or estimate the probability of having a fire with those specifications. This process of specification usually requires the analyst to address three stages of fire:

- What are the initial heat source, the initial fuel source, and the circumstances that bring them together? These are the basics of the initiating fire, and they need to be specified so that fire incident databases can be used as a major source for estimating probabilities.
- What are the factors that will determine whether and how quickly fire will spread from the first item to the product, if the product is not the first item ignited?
- What are the characteristics of the room or area of origin and its fuel packages and surfaces that will determine how large the fire will grow and whether, and how quickly, it will reach flashover and leave the room?

These three questions reflect the three states at which a burnable product may become involved in a fire: as the first item ignited, as a secondary item ignited by exposure to other items ignited earlier, or as part of a room that has gone to flashover, when everything that can burn will burn.

Two general approaches can be used to set up the model of these stages. One is to use surveys of fuel loads, room configurations, and the like. Then, one can run a fire-growth model with these specifications. This approach works well for fire-hazard assessment. The drawbacks of this approach for fire-risk assessment are the following: that the magnitude of the data requirements is extremely large; that such survey data is very scarce, and, when it exists, almost never captures the variations in practice that produce different probabilities and different fire outcomes; and that the probability of ignition is probably not constant from one configuration to another nor susceptible to estimation from any existing fire incident databases. If this approach is used, it will tend to force the analyst away from some of the essentials of fire-risk analysis (i.e., a suitably diverse set of scenarios and an adequate attention to the role of probabilities).

The other general approach is to infer patterns of fuel loads and room configurations from fire loss experience. The logic used here is as follows: Recent fires were produced by recent fuel load and room layout practices. What would those practices have to be in order to produce the observed fires? A critical element in this approach is data on the final extent of flame damage, which is captured in the major fire incident databases, as follows:

- Confined to object of origin
- Confined to area of origin
- Confined to room of origin
- Confined to fire-rated compartment of origin
- Confined to floor of origin
- Confined to building of origin
- Extended beyond building of origin

One can assume that a fire confined to object of origin involved only the first item ignited and that a fire extending beyond the room of origin reached flashover in the room of origin.

If the product was not the first item ignited but the fire spread beyond the object of origin, then the fire could have ignited the product through radiant exposure. One can estimate the probability that this will occur using a calculation procedure based on the following four elements:

- For each type of item first ignited (e.g., trash), a set of estimated typical values for mass and burning properties, sufficient to estimate a rate of heat release curve for the product burning alone
- Ignitability characteristics of the product (i.e., critical radiant flux)
- For each type of item first ignited, a probability distribution on the distance from the item to the product, as a function of the type of room, with distributions based on survey data and expert judgment
- Established mathematical relationships showing the minimum distance at which ignition of a second item will occur, given the first item's burning characteristics and the second item's ignitability characteristics.

This second approach still needs the kind of property survey data required by the first approach, but far less of it because the only geometric information sought is distances between the product and other items. Even so, this is still a data-hungry approach that requires either survey data that may not exist or may be very expensive to collect or expert judgment that may be especially difficult to make.

As in so many other areas, the temptation will be to reshape the analysis to bypass elements that cannot now be modeled with confidence. However, the analysis must somehow provide a valid basis for combining different product-

burning properties, and the phenomenon of secondary ignition is central to any evaluation of the product's relative ignitability.

Regardless of the method used to assemble fuel load and geometry data, they must be converted into physical descriptions of design fires, chosen to represent the selected scenarios. Fuel load in the room of origin primarily influences the growth stage of the fire and the duration of burning when the room reaches full involvement. The growth stage may be reducible to one of a small number of generic fire-growth curves.

The primary importance of the appropriate selection of the design fire's growth is in obtaining a realistic prediction of detector and sprinkler activation, time to start of evacuation, and time to initial exposure of occupants.

In 1972, Heskestad first proposed that, for these early times, the assumption that fires grow according to a power-law relation works well and is supported by experimental data (4). He suggested constructing design fires of the form

$$Q = \alpha t^n$$

where Q is the rate of heat release (kW), α is the fire intensity coefficient (kW/s^n), and t is the time (s).

Later, it was shown that for most flaming fires (except flammable liquids and some others), $n = 2$, the so-called t^2 growth rate (5). A set of specific t^2 fires labeled slow, medium, and fast, with fire intensity coefficients such that the fires reached 1055 kW (1000 Btu/s) in 600, 300, and 150 s, respectively, was proposed for the design of fire-detection systems (6). Later, these specific growth curves and a fourth called "ultrafast," which reaches 1055 kW in 75 s, gained favor in general fire-protection applications (7).

The slow curve is appropriate for fires involving thick, solid objects (e.g., solid wood table, bedroom dresser, or cabinet). The medium growth curve is typical of solid fuels of lower density (e.g., upholstered furniture and mattresses). Fast fires are thin, combustible items (e.g., paper, cardboard boxes, draperies). Ultrafast fires are some flammable liquids, some older types of upholstered furniture and mattresses, and other highly volatile fuels.

In a highly mixed collection of fuels, selecting the medium curve is appropriate as long as there is no especially flammable item present. It should also be noted that these t^2 curves represent fire growth starting with a reasonably large, flaming ignition source. With small sources, there is an incubation period before established flaming, which can influence the response of smoke detectors (resulting in an underestimate of time to detection). This can be simulated by adding a slow, linear growth period until the rate of heat release reaches 25 kW.

This specific set of fire-growth curves has been incorporated into several design methods, such as for the design of fire-detection systems in NFPA 72, *National Fire Alarm Code* (8). They are also referenced as appropriate design fires in

several international methods for performing alternative design analyses in Australia and Japan, and in a product fire-risk analysis method published in the United States (9). Whereas in the Australian methodology, the selection of growth curve is related to the fuel load (mass of combustible material per unit floor area), this is not justified because the growth rate is related to the form, arrangement, and type of material and not simply its quantity. Consider 10 kg (22 lbs) of wood, which may be arranged in a solid cube, as sticks arranged in a crib, and as a layer of sawdust. These three arrangements would have significantly different growth rates while representing identical fuel loads.

Still other phenomena must be reduced to assumptions for modeling purposes. The following are examples: For a fire that does not reach flashover, what is the physical measure (e.g., temperature) of its peak size? What stops the fire and what characteristics of fire development (e.g., burning time, detector activation, fire size) trigger fire suppression? (This is important in order to know when to stop the fire if the product is changed.) What is the fire's profile after it reaches its peak? Is there an initial smoldering phase, and, if so, how long is it and what is the fire profile during this period? Each of these questions needs to be answered through a crosswalk between, first, the physical parameters measured in tests and used in models and, second, the parameters recorded in fire incident databases, because the latter is always needed to calibrate the probability estimation.

Once all of the surface area of the fuel is burning, the heat-release rate goes into a steady burning phase. This may be at a subflashover or a postflashover level; the former will be fuel controlled and the latter ventilation controlled. It should be obvious from the model output (for oxygen concentration or upper-layer temperature) in which condition the fire is burning.

Most fires of interest will be ventilation controlled, and this is a distinct advantage, because it is easier to specify sources of air than details of the fuel items. This makes the prediction relatively insensitive to both fuel characteristics and quantity, as adding or reducing fuel simply makes the outside flame larger or smaller. Thus, for ventilation-controlled situations, (a) the heat-release rate can be specified at a level that results in a flame out the door and (b) the heat released inside the room will be controlled to the appropriate level by the model's calculation of available oxygen. If the door flame is outside, it has no effect on conditions in the building; if in another room, it will affect that and subsequent rooms. For the much smaller number of fuel-controlled scenarios, values of the heat-release rate per unit area at a given radiant exposure (from ASTM E1354, *Standard Test Method for Heat and Visible Smoke Release Rates for Materials and Products Using an Oxygen Consumption Calorimeter*) can be found in handbooks and used with an estimate of the total fuel area (10).

Burning rate declines as fuel is exhausted. In the absence of experimental data, an engineering approximation specifies this decline as the inverse of the growth curve; this means that fast growth fuels decay fast and slow decay slow. It

is often assumed that the time at which decay begins is when 20% of the original fuel is left. Although these are assumptions, they are technically reasonable.

This decay will proceed even if a sprinkler system is present and activated. A simple assumption is that the fire immediately goes out, but this is not conservative. A National Institute of Science and Technology (NIST) study documents a (conservative) exponential diminution in burning rate under the application of water from a sprinkler (11). Because the combustion efficiency is affected by the application of water, the use of values of soot and gas yields appropriate for post-flashover burning would represent the conservative approach in the absence of experimental data.

A. Scenarios: Beyond the First Room

The dimensions used to define the different occupancy scenarios need to be dimensions that are relevant to fire development. Most of these dimensions will be one of three types:

- Building dimensions and geometry: Dimensions of rooms and other areas in which fire may grow or smoke may spread
- Openings: Dimensions of openings between rooms and areas relating to paths of flame or smoke spread and sources of air to feed the fire
- Room linings: Thermal properties of rooms that may bear on burning at and after flashover.

1. Building Dimensions and Geometry

The overall building size and geometry can be structured into a series of questions on which data must be sought and decisions made. The first is the range of variation in the number of floors. After determining this point, the user must specify a number of floors for each occupancy scenario.

The second is a room layout for each floor. Room heights and the sizes of openings connecting rooms tend to be standardized by common industry practices, so there may be no need to consider variations. For other factors (e.g., the number and sizes of rooms), there usually is too much variation in practice and too little data on the relative likelihood of these variations to do much more than (a) estimate one or two values for the number of rooms or the total square feet per floor and (b) use expert panels to develop detailed layouts for the purpose of modeling and analysis of the rooms or spaces specified in (a).

However, panels of people who are experts on buildings of a certain type are likely to think in terms of the characteristics of the particular buildings they know best. They may therefore give estimates biased toward characteristics of new con-

struction or characteristics of the buildings they live in or frequent. Fires are more likely to occur in smaller, less prestigious units in any property class. The expert panel needs to be continually reminded to adjust their perspective to think in terms of those kind of buildings.

2. Openings

There usually will be some information on the sizes of doors and windows, because construction practices are highly standardized even beyond code requirements. However, in a fire, the openings will depend critically on whether and how much key doors and windows are open. There is little or no data on this point for any occupancy. It may be possible to ignore windows, because there are studies indicating that windows affect most fires only after the point in time that fire severity has been determined. (However, the few exceptions will tend to be very large fires, so the reasonableness of an assumption excluding windows will need to be rechecked for any analysis.) For doors, there are no such simple assumptions and, hence, no simple approach short of large-scale property surveys or other special fire data collection projects.

In fire-hazard assessment, one makes conservative assumptions (i.e., those that present the greatest fire challenge), whereas in fire-risk analysis, one uses a best estimate, without conservatism. However, an assumption that might be made in fire-hazard analysis because it is conservative may also turn out to be a reasonable best estimate for fire-risk analysis if it reflects a pattern in actual fire experience. If a certain arrangement could produce more serious fires, it qualifies as a conservative assumption for fire-hazard analysis. If that same arrangement is producing more serious fires, then it is more likely that that arrangement is present when a reported fire occurs than that it is present in buildings in general, and one could be justified in assuming that that arrangement is likely, in a fire-risk analysis.

However, this line of reasoning has limits. Suppose that open doors is the conservative assumption, but that we know that doors tend to be open only 5% of the time. In that case, the fire-risk analysis could reasonably assume that doors are open 10–20% of the time, reflecting the likelihood that open doors will be more likely in reported fires than in buildings, in general. However, the typical situation would still be closed doors.

The analysis would need to have scenarios with open doors and scenarios with closed doors, because neither condition is dominant enough to justify omitting the other condition for a variable (i.e., whether doors are open) that is so influential on final fire size; or, it might be possible to use one condition, consisting of doors open slightly, trying to seek a single physical condition that will reproduce the appropriate average between fully open and fully closed. Either way, considerable judgment would be needed.

Remember that if an "average" value is used, the analyst is implicitly assuming that the fire severity associated with that average value is equal to the average of the fire severities associated with all the individual values that occur. In mathematics, this is sometimes called assuming that the average of the function equals the function of the average, and it is not usually the case. The analyst has to make the case that the assumption is reasonable in the situation being analyzed.

3. Room Linings

Linings of rooms and other areas need to be addressed in terms of the thermal properties required for calculation of time to flashover, speed of vertical flame spread, and the like.

Room and area linings for most occupancies are tightly regulated by codes. However, some of the most important occupancies (e.g., dwellings) are not so covered, and even for those that are, one must allow for a significant probability that the codes will not have been in force when fire occurs. Unfortunately, there is little or no data on the probabilities of different combinations of fuels in particular occupancies, and there is only very limited, dated information on typical or average fuel loads and only for some occupancies.

B. Scenarios: Exposure of People or Property

In order to translate model or test outputs on the physical characteristics of fire, as a function of location and time, into end measures of human or property loss, one must address (a) the locations of people or property as a function of time and (b) the damage or loss consequences to people or property of the different possible physical characteristics of fire (e.g., temperature, quantities of toxic gases by type, corrosive properties, and quantities of smoke). The methods for doing this are not extensively developed, except for deaths. Therefore, this section will focus on that outcome.

Occupant exposure depends on (a) initial locations of the occupants relative to the fire and (b) their escape behavior. A complete specification of the number of occupants with their initial locations and other characteristics is called an occupant set. The user must define a group of occupant sets. For risk assessment, the occupant sets analyzed must collectively represent all possible combinations of people and their characteristics and locations, and one must estimate probabilities for each. These must then be joined to a model of occupant behavior. (See Ref. 2 for a list of evacuation models.)

Occupant behavior models consist of a set of rules for calculating the locations of occupants at a time, t, as a function of their locations, other occupant characteristics, and fire characteristics at the time stage just prior to t. Some such models track occupants individually; others give only the number of people at each

location. Some, but not all, models include interactions among occupants, such as congestion or queuing effects or behavioral rules based on relationships between occupants (e.g., parents who seek to rescue babies). The more comprehensive the model may be in capturing potentially important phenomena, the more computationally demanding it will be and the more data it will demand, possibly including data that are not readily available. As in all other aspects of analysis, trade-offs must be made in the modeling.

A brief summary of the steps required for fire-risk or fire-hazard assessment is as follows, where at each step, fire-risk assessment requires the estimation of probabilities:

- For each occupant set, specify the number of people present in the building.
- Specify relevant occupant characteristics, including ages and relationships of occupants, time of day, and occupant conditions.
- Specify occupant activity as a function of time of day and of the occupant characteristics specified in the previous step.
- Specify occupant location given occupant activity and other occupant characteristics. (If every activity implies a unique location, this will reduce to a crosswalk.)

C. Scenarios: Fire-Protection Systems and Features

The following requirements are straightforward, in principle, but necessary models or data are often sketchy:

- For each type of fire-protection system (e.g., detectors, sprinklers, smoke control systems) or feature (e.g., fire doors), identify a range of alternatives. These alternatives must address not only variation in the type and coverage of system or feature used (e.g., quick response versus conventional sprinkler) but also variations in operational status (e.g., fully operational versus water turned off).
- For each alternative, probabilities will be needed for fire-risk assessment. As in the other parts of the analysis, start with representative national fire incident databases for best estimates, then add needed detail using other databases and expert judgment.
- For each alternative, specify rules for how the system or feature under that alternative will affect the fire development, the evacuation, or other conditions being tracked. Often, this will be fairly simple. One could assume that a fully operational sprinkler system will activate once a specified set of fire conditions is reached and, once activated, will totally and immediately stop the fire, except for certain specified fire scenarios

(e.g., fire origin in concealed spaces) when its effect will be only to block fire entry into sprinklered areas. One could assume that a full-coverage automatic detection system will activate once a specified set of smoke or heat conditions are reached and, once activated, will alert everyone in the building to the fire, leading anyone not already in motion in the occupant evacuation model to begin evacuating.

VIII. IDENTIFY TEST METHODS, MODELS, AND CALCULATION METHODS

A. Models of Fire Development and Spread of Fire Effects

Fire is a dynamic process of interacting physics and chemistry; thus, predicting what is likely to happen under a given set of circumstances is daunting. The simplest of predictive methods are the (algebraic) equations. Often developed wholly or in part from correlations to experimental data, they represent, at best, estimates with significant uncertainty. Yet, under the right circumstances, they have been demonstrated to provide useful results, especially where used to assist in setting up a more complex model. For example, Thomas' flashover correlation (12) and the McCaffrey–Quintiere–Harkleroad (MQH) upper-layer temperature correlation (13) are generally held to provide useful engineering estimates of whether flashover occurs and peak compartment temperatures.

Where public safety is at stake, it is inappropriate to rely solely on such estimation techniques for the fire development/smoke filling calculation. Here, only fire models (or appropriate testing) should be used. Single-room models are appropriate where the conditions of interest are limited to a single, enclosed space. Where the area of interest involves more than one space, and especially where the area of interest extends beyond a single floor, multiple-compartment models should be used. This is because the interconnected spaces interact to influence the fire development and flows.

Many single-compartment models assume that the lower layer remains at ambient conditions [e.g., available safe egress time (ASET)] (14). Because there is little mixing between layers in a room (unless there are mechanical systems), these models are appropriate. However, significant mixing can occur in doorways, so multiple-compartment models should allow the lower layer to be contaminated by energy and mass.

The model should include the limitations of burning by available oxygen. This is straightforward to implement (based on the oxygen consumption principle) and is crucial to obtaining an accurate prediction for ventilation-controlled burning. For multiple-compartment models, it is equally important for the model to track unburned fuel and allow it to burn when it encounters sufficient oxygen

and temperature. Without these features, the model concentrates the combustion in the room of origin, overpredicting conditions there and underpredicting conditions in other spaces.

Heat-transfer calculations take up a lot of computer time, so many models take a shortcut. The most common is the use of a constant "heat loss fraction," which is user selectable [e.g., ASET or consolidated compartment fire model (CCFM)] (15). The problem is that heat losses vary significantly during the course of the fire. Thus, in smaller rooms or spaces with larger surface-to-volume ratios where heat loss variations are significant, this simplification is a major source of error. In large, open spaces with no walls or walls made of highly insulating materials, the constant heat loss fraction may produce acceptable results; but, in most cases, the best approach is to use a model that does proper heat transfer.

Another problem can occur in tall spaces (e.g., atria). The major source of gas expansion and energy and mass dilution is entrainment of ambient air into the fire plume. It can be argued that, in a very tall plume, this entrainment is constrained; but most models do not include this. This can lead to an underestimate of the temperature and smoke density and an overestimate of the layer volume and filling rate—the combination of which may give predictions of egress times available that are either greater or less than the correct value. In the consolidated fire growth and smoke transport model (CFAST), this constraint is implemented by stopping entrainment when the plume temperature drops to within one degree (Kelvin) of the temperature just outside the plume, where buoyancy ceases (16).

Only models that are rigorously documented should be allowed in any application affecting final product choices. It is simply not appropriate to rely on the model developer's word that the physics is proper. This means that the model should be supplied with a technical reference guide that includes a detailed description of the included physics and chemistry (with proper literature references), a listing of all assumptions and limitations of the model, and estimates of the accuracy of the resulting predictions, based on comparisons to experimental data. Public exposure and review of the exact basis for a model's calculations, internal constants, and assumptions are necessary for it to have credibility.

Although it may not be necessary for the full source code to be available, the method of implementing key calculations in the code and details of the numerical solver utilized should be included. This documentation should be freely available to any user of the model and a copy should be supplied with the analysis as an important supporting document.

Even if the model is correct, the results can be seriously in error if the data input to the model does not represent the condition being analyzed. Proper specification of the fire is the most critical. Next in importance is specifying sources of air supply to the fire (i.e., not only open doors or windows but also cracks behind trim or around closed doors). Most (large) fires of interest quickly become ventilation controlled, making these sources of air crucial to a correct prediction. The

most frequent source of errors by novice users of these models is to underestimate the combustion air and underpredict the burning rate. Two other important items of data are ignition characteristics of secondary fuel items and the heat-transfer parameters for ceiling and wall materials.

B. Models of Evacuation and Behavior

The prediction of the time needed by the building occupants to evacuate to a safe area is performed next and compared to the time available from the previous steps.

Whether the evacuation calculation is done by model or hand calculation, it must account for several crucial factors. First, unless the occupants see the actual fire, there is time required for detection and notification before the evacuation process can begin. Next, unless the information is compelling (again, they see the actual fire), it takes time for people to decide to take action. Finally, the movement begins. All of these factors require time and that is the critical factor. No matter how the calculation is done, all of the factors must be included in the analysis to obtain a complete picture. An excellent discussion of this topic is found in Refs. 17 and 18.

The process of emergency evacuation of people follows the general concepts of traffic flow. There are a number of models that perform such calculations that may be appropriate for use in certain occupancies. Most of these models do not account for behavior and the interaction of people (providing assistance) during the event. This is appropriate in most public occupancies where people do not know each other. In residential occupancies, family members will interact strongly; in office occupancies, people who work together on a daily basis would be expected to interact similarly. The literature reports incidents of providing assistance to disabled persons, again especially in office settings (19). If such behavior is expected, it should be included, as it can result in significant delays in evacuating a building.

Another situation where models (e.g., Fahy's EXIT89) are preferred to hand calculations is with large populations where congestion in stairways and doorways can cause the flow to back up (20). However, this can be accounted for in hand calculations, as well. Crowded conditions, as well as smoke density, can result in reduced walking speeds (21). Care should be exercised in using models relative to how they select the path (usually the shortest path) over which the person travels. Some models are optimization calculations that give the best possible performance. These are inappropriate for a fire-risk or fire-hazard assessment, unless a suitable safety factor was used.

Evacuation calculations are sometimes simple enough to be done by hand. The most thorough presentation on this subject (and the one most often used in alternate design analysis) is that of Nelson and MacLennen (22). Their procedure explicitly includes all of the factors discussed previously, along with suggestions

on how to account for each. They also deal with congestion, movement through doors and on stairs, and other related considerations.

C. Models of the Effect of Exposure

In most cases, the exposure will be to people, and the methods used to assess the impacts of exposure of people to heat and combustion gases involves the application of combustion toxicology models. The HAZARD I software package contains the only toxicological computer model, called TENAB (23), which is based on research at NIST on lethality to rats (24) and by Purser on incapacitation of monkeys (25). These methods can also be applied in hand calculations, utilizing the material by Purser and the equations found in Ref. 22. TENAB accounts for the variation in exposure to combustion products as people move through a building, by reading the concentrations from the fire model in the occupied space during the time the person is in that space. If the person moves into a space with a lower concentration of carbon monoxide, the accumulated dose actually decreases. Details such as these ensure that the results are reasonable. It is important that these details be observed in hand calculations, as well.

Assessing the impact of exposure on sensitive equipment is more difficult, because little data exist in the literature on the effects of smoke exposure on such equipment. Of particular importance here is the existence of acid gases in smoke, which are known to be corrosive and especially harmful to electronics. Fuels containing chlorine [e.g., poly(vinyl chlorides)] have been studied. However, unless the equipment is close to the fire, acid gases, and especially HCl, deposit on the walls, which lower the concentration to which the equipment may be exposed. CFAST in the HAZARD package contains a routine that models this process and the associated diminution of HCl concentration.

IX. OTHER ISSUES IN ASSESSMENT

A. How Much Hazard or Risk Is Acceptable?

Acceptable risk is a term used when treating risk as a constraint. This method may seem attractive because it refuses to consider costs until or unless a sufficient degree of fire safety has been provided. In an acceptable risk approach, a certain level of risk is defined as acceptable; then all alternatives meeting that level are evaluated strictly on the basis of cost.

This approach can produce unsatisfactory results. If risk is greater than the acceptable level by even a small fraction, no cost is too great to reach acceptable risk. If risk already is acceptably low, not a nickel more should be spent, no matter how much more fire safety could be purchased for very little. This means that the selected level of acceptable risk is often set with an eye toward affordability and may be reset if technology changes. In effect, this makes the acceptable risk

approach a kind of backdoor cost/benefit analysis and runs counter to most approaches to decision making in business.

When acceptable risk is not defined in terms of affordable risk, it is often defined in terms of (a) historically acceptable risk (i.e., anything in use for a long time is all right), which may be overturned if public understanding of the magnitude of the risk changes dramatically or (b) unavoidable risk, such as the use of background radiation levels as a guide for acceptable exposure to medical x-rays. In fire protection, acceptable risk has sometimes been inferred from provisions of NFPA codes and standards. The most extreme version of an acceptable risk approach is a minimum risk approach, in which cost is not considered unless all feasible safety improvements have been made.

A logical complement to the acceptable risk approach would be an acceptable cost approach, in which the greatest risk reduction available within the fixed-cost budget (but no more) would be sought. Although this approach is rarely mentioned in the literature, it almost certainly describes the way some decisions are made. In Canada, the public cost per death avoided for several mandated safety products (e.g., ground-fault circuit interrupters, airbags) was computed and was found to be reasonably consistent ($\sim$\$1M–2M per death avoided). This figure was then used as a gauge for public acceptance of other safety regulation.

B. Value of Life

Determining the acceptable level of risk or hazard may require a comparison of predicted fire deaths or injuries to predicted costs or other monetary measures.

The explicit or implicit assignment of monetary values to lives saved and injuries averted is a difficult step that many people find distasteful or even immoral. The first and most important point to make is that individuals are not being asked to name a price for which they would be willing to die or suffer crippling injury. Instead, they are being asked to name a price they would be willing to accept to allow their current low risk of incurring death or injury in fire to increase or what they would pay to make that risk still smaller. With a resident population of about 260 million and an annual fire death toll in the range of 4000–5000, an average U.S. citizen has less than 1 chance in 50,000 each year of dying in a fire. Even for the highest-risk groups, the risk is probably less than 1 chance in 5000 each year, or less than 1 chance in 65 over an entire lifetime. A person could rationally attach a price of 10% or 50% change in such a risk and still be consistent in believing life (i.e., the certainty of losing it) is beyond price. A rational person would pay much more to reduce the probability of dying from 1.0 to 0.8 than he or she would pay to cut that risk from 0.3 to 0.1.

If that point is made, the next task is identifying what particular figures should be used for the value of life and the value of injury when considering alternatives that change risks in the range characteristic of fire risk. In the 1960s and earlier, the value of life was generally calculated on the basis of discounted fore-

gone future earnings. This approach implicitly assigned no value to the lives of retired people and full-time homemakers and negligible value to the lives of older workers and young children. Such distinctions were philosophically objectionable.

Even for prime wage earners, the methodology did not afford any guarantee that the value obtained would match the price people wanted to pay for risk reduction. In recent years, this approach has been largely abandoned in favor of calculations of willingness to pay to reduce risk of death. Practically speaking, the shift in approach roughly tripled the standard values of life (26).

For all the philosophical disagreements, the actual values attached to lives saved, however calculated, tend to be concentrated within two orders of magnitude. Most studies estimate the value of life in hundreds of thousands of dollars or millions of dollars. Some of the higher values are taken from jury awards that compensate deaths. Few estimates go as high as tens of millions of dollars or as low as tens of thousands of dollars.

It is difficult to set up fully persuasive methodologies to assess a popular consensus on value of life because people do not like to think about death. If asked about the value of a whole life, they refer to the sanctity of life and say the value is infinite. If asked about the value of a shift in the risk of dying, they find it difficult to relate to such a choice. If presented with forced-choice situations that contain implicit values of life, they give answers that can reflect the way the questions were posed. Nevertheless, a 1988 study of assessments used in evaluating a wide range of proposed federal regulations concluded that "there has recently been some convergence around a figure of $1 to $2 million per statistical life" (27). In 1998, a value of $3 million would reflect inflation since the 1988 study.

Another alternative is to use a value per year of life saved. However, use of life-year value tends to give more credit to saving children (by up to double, as their expected life spans are about double those of the population at large) and less credit to saving older adults (by a factor of 4 or more). Fire safety in schools would be boosted and fire safety in nursing homes might be scaled back if life-year value calculations were used.

Even after deciding to use willingness to pay as the standard for value of life, some difficult technical problems remain. One is the question of whether to calculate separately the willingness to pay for each individual (or each major group) affected by a proposed change. In an analysis aimed at the individual property owner or manager, such differentiation is unavoidable and should be an explicit, or at least implicit, part of any analysis of the market for a new product, system, or approach.

There also have been several studies of factors that affect willingness to pay. Willingness to pay is lower for the poor, older Americans, the seriously ill or handicapped, and risk-takers. For the poor, of course, ability to pay is lower, too. For older Americans and the seriously ill, the lower value given to life seems to reflect the fact that the quantity (for the older American) or the quality (for the sick) of

life remaining is well below the national norm. However, all these groups with lower willingness to pay also tend to have relatively high risks of becoming fire fatalities. They are precisely the groups to target if total lives saved were the criterion of choice. Conversely, the people most willing to pay—affluent, healthy, risk-averse, young heads of families—are the ones least likely to benefit because their current risks of dying in fire are already below average.

Another reason for variations in the willingness to pay involves the nature of the risks rather than the characteristics of those who experience these risks. Risks that are voluntary, nonessential, occupational, or results of product misuse are deemed less serious than risks that are involuntary, essential, public, or results of normal product use. A risk of death to someone who lives near a nuclear reactor is valued more highly than an equal risk of death to someone who works in a coal mine.

The difference is based on the assumption that occupational risks are more likely to be voluntary and more likely to be financially compensated. Both of these assumptions are questionable. Workers in hazardous occupations such as mining may have few realistic occupational alternatives, whereas residents of hazardous areas, like floodplains, may have many alternative places to live and may have received financial compensation in the form of lower housing costs that at least equal any financial benefits received by the workers.

Similarly, risks of death associated with voluntary nonessential activities, such as smoking and hang gliding, are valued less than equal risks associated with voluntary but essential activities, such as driving a car. In fire risk, this argument appears in the debate over the fairness of imposing ignition resistance standards (and accompanying costs) on all mattresses to protect people who choose to smoke in bed.

Deaths occurring in major multifatality incidents are valued differently—and generally more highly—than deaths occurring in smaller incidents. Major incidents are termed dread hazards in the risk analysis literature; it is the factor of dread—the greater fear of death occurring in a major incident—that inflates the value of risk to such cases. The effect of major incidents on families and communities has been used to argue for both higher and lower weighting of such deaths—higher because familial bloodlines may be extinguished, lower because multiple deaths in one family mean fewer survivors to mourn per fatality (28).

Dread incidents constitute an especially dramatic example of the phenomenon of risk aversion. For example, most people feel that if loss A is 10 times as great as loss B but only one-tenth as likely, losses A and B still are not equally onerous. The general public tends to be more concerned about fire scenarios that may kill, say 100 people once every 3 years than they are about fire scenarios that kill 1 person at a time every week, year after year.

Technical adjustments can be made to incorporate some risk aversion into a benefit calculation. Such adjustments will have less effect on dwelling-fire risk

calculations, where really large incidents are impossible, than on risk calculations for large residential (e.g., hotel), institutional, or public assembly properties.

Values for injuries avoided can be estimated more directly than values for fatalities avoided because direct costs such as medical expense and lost wages seem more appropriate as indicators of value. A survey was used to estimate direct injury-related costs for residential fires (29). Based on their figures, after adjusting for inflation and for the fact that their cost-per-injury figures are dominated by very small injuries from unreported fires, an estimate of $5000 might be obtained for actual costs per injury received in a reported fire. Willingness to pay to avoid an injury is greater because of pain and suffering considerations, so a figure of $35,000 was derived in the late 1980s by economists at the U.S. Consumer Product Safety Commisison (30).

This average is based on a highly skewed distribution. The vast majority of injuries can be valued in the low hundreds of dollars or less, but a small number of serious burn injuries each year—considerably fewer than the corresponding number of fire fatalities—can cost hundreds of thousands or even millions of dollars in medical expenses. These few injuries account for most of the overall cost average. This suggests that analyses of expected impacts of new systems or programs on injuries should, if possible, separate serious and nonserious injuries when average values are used, to make sure that the average values are not understated as typical values.

Finally, even with the substantial ranges shown for cost per fatality or per injury, it will be clear that deaths and injuries dominate loss, expressed in dollar terms, in home fires but not in fires in any other type of building. In a typical year, home fire deaths outnumber fire deaths in other types of buildings by 20 to 1. For injuries, the ratio is in the range from 5 to 1 to 7 to 1. But for property damage, the ratio is less than 2 to 1 in favor of homes. Even after considering that the public demands greater safety outside their homes—or at least requires lower objective risk in order to feel safe—and writes codes to reflect that it is still true that fire risk assessments outside the home will be driven by economics—by dollars spent versus dollars that could be lost. Concerns over corporate image or liability are real, but they operate more as second-order effects, so long as corporate decisions do not move too far away from the levels of safety embodied in current prescriptive codes. This increases the importance of doing a fair, balanced, and accurate job of quantifying and analyzing costs.

X. WHAT TO DO WITH COST

Costs may be divided into (a) initial costs of the proposed changes being studied, (b) the ongoing costs of these changes once they have been made, and (c) the

ripple effects of other costs, such as the need to increase the water supply to support a sprinkler system. The last could involve cost increases or cost reductions, including calculations of costs for many years into the future. To make this task manageable, the analysis can be set up in terms of the normal periods of maintaining, repairing, and replacing the items being analyzed. This is called life-cycle costing. An overview of major components of each of these three types of costs is shown in the following subsections.

A. Initial Costs of Changes Being Studied

1. Equipment costs. For new products, it may be necessary to estimate what costs will be when mass production is under way. In many cases, the mass production cost continues to drop as further development occurs. (Smoke detectors have shows this pattern, for example.)
2. Installation costs. Estimation of costs of installation may require an analysis of the steps required for installation, because the person-hours and skills required for those steps may be higher or lower than for comparable products already in use. (For example, plastic pipe may be faster to install than iron pipe, and it may require less time-consuming effort to protect carpets and furniture from soiling during installation.) Labor costs per hour may vary considerably from one place to another, as may overhead rates; these variations argue in favor of a serious effort to collect representative data.
3. Financing costs. These will be relevant if the systems are financed through time-payment plans (e.g., as part of what is covered by the building mortgage).
4. Permit/license costs. There may be some one-time fees required to install the systems.
5. Some costs offset in resale. If the new systems and features add to the resale value of the property, this will partially offset the initial costs.

B. Ongoing Costs of Changes Being Studied

1. Operating costs. A new system or product may need labor, power, or some other continuing input to operate. These costs need to be included.
2. Inspection and testing costs. Many systems require periodic inspection and testing after installation. These costs should be included. Labor usually will be the main cost element, but some tests (such as sprinkler tests) may involve materials costs, and other tests may require destruction of a sample of system components that would need replacement.

3. Repair, maintenance, and replacement costs. Most systems will require repair and maintenance, and if the study period is long enough, periodic replacement will need to be considered.
4. Costs of nonfire damage caused by the systems. An example would be water damage due to accidental discharge of a sprinkler.
5. Permit/license costs. An example would be the standby water charge levied in some jurisdictions on buildings equipped with sprinklers.
6. Salvage revenues for cost offsets. Equipment that is replaced may be re-sellable. If so, salvage revenues help reduce net system costs.

C. Ripple Effects on Other Building Costs

1. Costs of supporting systems. Many new products may require replacement, modifications, or addition of critical supporting systems (e.g., extra water supply for home sprinkler system in a rural area). The equipment and installation costs of these changes in supporting systems need to be identified and included as do any changes in operating costs, repair and maintenance costs, inspection and testing costs, and so forth for the modified supporting systems, and any changes in these ongoing costs for unmodified supporting systems.
2. Special incentives or credits. Insurance premium reductions that reflect the expected reduction in direct loss should be counted in the loss evaluation model. Extra reductions offered as inducements to buy systems, as well as incentives or credits in property or income taxes, should be counted here.
3. Property value and tax impacts. Changes in property taxes reflecting changed property value assessments should be considered. There may be tax consequences if the features add value to the property.
4. Changes in land costs or required building features. Added safety features may permit trade-offs in the form of increased density or reduced requirements for other building features. These need to be accommodated as costs, and any trade-offs in other safety features need to be addressed in the loss evaluation models as well.
5. Changes in costs of public fire protection. If buildings in a group receive similar modifications, it may be possible to accept longer response times or reduced sizes of fire suppression teams, resulting in reduced costs of public fire protection.

These lists are not exhaustive, but they indicate the need to estimate the effects of different decisions and assess their cost impacts.

Fire-risk assessment will produce time streams of costs and risk-reduction benefits; that is, year-by-year estimates of costs and of reductions in fire deaths, injuries, and property damage, with the latter expressed as total monetized losses.

To compare the costs to the benefits, the two time streams need to be combined into a single, manageable indicator of net benefits.

To compare future and present costs and benefits, it is necessary to decide what the future costs and benefits are worth in the present. This involves the concept of opportunity cost. Suppose $20 was spent now on a fire safety system and $20 received back 10 years later in the form of reduced property damage in a fire. This would not be a breakeven proposition because alternative investments could pay interest over that period.

Assumptions about the attractiveness of such investments are reflected in an assumed discount rate—a proportion between 0 and 1 used to reduce the value of future costs and benefits. Most fire-risk-reducing strategies involve greater costs than benefits in the near years and greater benefits than costs in the later years; this makes the discount rate a critical factor in overall assessment of whether the benefits justify the costs. Also, even if opportunity costs were not involved, there would be a cost associated with delayed consumption. All other things being equal, people usually prefer to have goods and services now rather than later, and a discount rate reflects that fact.

If a cost is incurred 10 years from now, for instance, the discount rate must be applied 10 times to translate that cost into a figure comparable with today's costs. This figure is called the present value of a future cost or benefit. It is calculated as the discount rate raised to a power equal to the number of years in the future when the cost or benefit will occur, then multiplied by the value of that cost or benefit.

A reasonable discount rate can be assumed for the purpose of analysis or can be calculated as the discount rate required just to balance benefits and costs. If the latter is done, the derived discount rate is called the internal rate of return. It can be used to compare alternatives in the same way that a benefit/cost ratio can be used.

The two principal objections to discounting of future safety benefits are (a) the possibility of very large, perhaps even irreversible, effects at a remote point in the future and (b) the cumulative effects of the short-term biases induced by rigorous application of discounted assessments. The first objection is not a great concern for fire-risk problems because fire does not produce irreversible effects on the scale contemplated by this argument. At most, several small towns could be wiped out by a wildfire (ignoring, for the moment, the possibility of wartime firestorms). Nevertheless, as a technical matter, it is worth considering the possibility that discount rates undervalue the real value people assign to events beyond the next decade or so. For example, most people would regard benefits in 105 years as equal to benefits in 100 years; but under constant discounting of say, 10%, the former would be only 59% percent of the latter (31).

As for the cumulative problems of short-term bias, this has been discussed more in the context of business research, development, and innovation in general than in regard to safety innovations in particular. In business, investments are ex-

pected to balance benefits and costs within 3–7 years, but many analysts believe such requirements are too demanding and tend, over time, to choke off truly dramatic breakthroughs. The result, in business, can be eventual loss of competitive edge to a competitor willing to take a longer view.

One pertinent article was particularly forceful on this point, arguing that the implied opportunity cost model underlying a short payback period requirement assumes a standard reference alternative investment that, contrary to the model's assumptions, is not itself immune to the cumulative effects of a stream of choices driven by short-term considerations (32). The fallacy, then, is in assuming that there always is an alternative investment that pays back in 3–7 years; the short-term-driven decisions may have the cumulative effect of eroding all such alternatives.

The technical approach to addressing this concern is to check the sensitivity of any conclusions to the use of a lower discount rate. Any innovation that year by year, after the initial cost period, produces more benefits than costs can be made to look attractive through the selection of a sufficiently low discount rate. It is risky, however, to use too low a discount rate, because that will give a misleading picture of what people will be willing to pay.

XI. UNCERTAINTY AND SENSITIVITY ANALYSIS

Uncertainty accountability refers to dealing with the uncertainty that is inherent in any prediction. In the calculations, this uncertainty is derived from assumptions in the models and from the representativeness of the input data. In evacuation calculations, there is the added variability of any population of real people. In building design and codes, the classic method of treating uncertainty is with safety factors. A sufficient safety factor is applied such that if all of the uncertainty resulted in error in the safe direction, the result would still provide an acceptable solution.

The report should include a discussion of uncertainty. This discussion should address the representativeness of the data used and the sensitivity of the results to data and assumptions made. If the sensitivity is not readily apparent, a sensitivity analysis (i.e., vary the data to the limits and see whether the conclusions change) should be performed. This is also a good time to justify the appropriateness of the model or calculation method.

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